# Independent Reliability Assessment of the Laser Transmitter for the ESA-NASA Laser Interferometer Space Antenna (LISA) Program


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# OUTLINE

- LISA Program Background
- NASA's LISA Laser Architecture
- NESC Assessment Study Scope & Approach
- NESC Assessment Summary
- Conclusions

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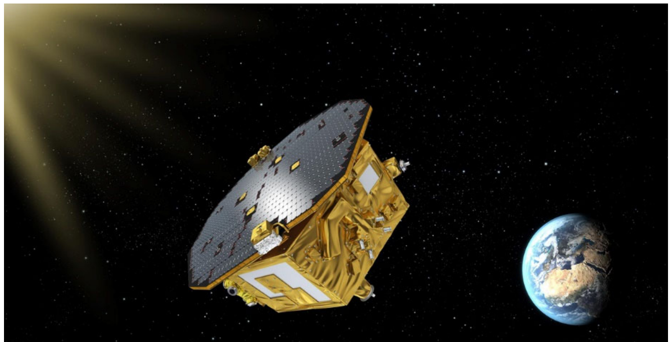
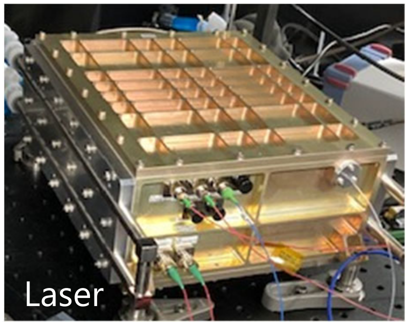
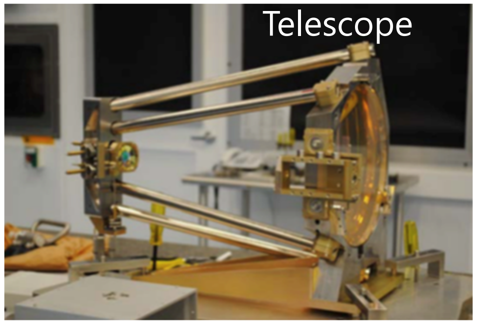
# LISA COLLABORATION

- Follow-on to LISA Pathfinder that demonstrated the concept and technology
- LISA is led by ESA, and is a collaboration between ESA, NASA, and international consortium of member states
- NASA and ESA are in negotiation regarding contributions from NASA. Potential major contributions are:
  - —Laser System
  - —Telescope System
  - —Charge Management System
- Need TRL 6 by Mission Adoption (June-Oct 2023)

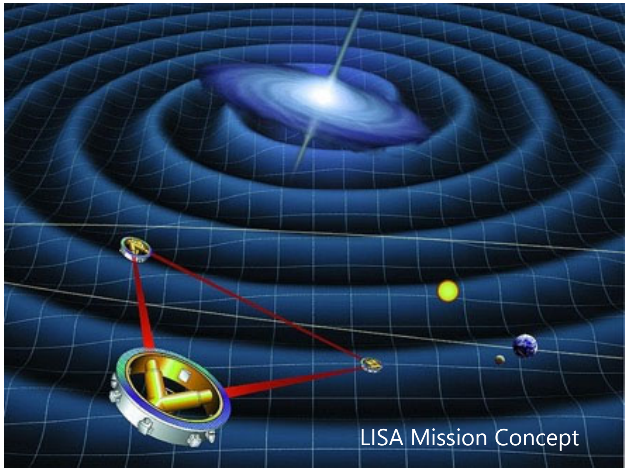

LISA Pathfinder Demonstrated in 2016 at L1

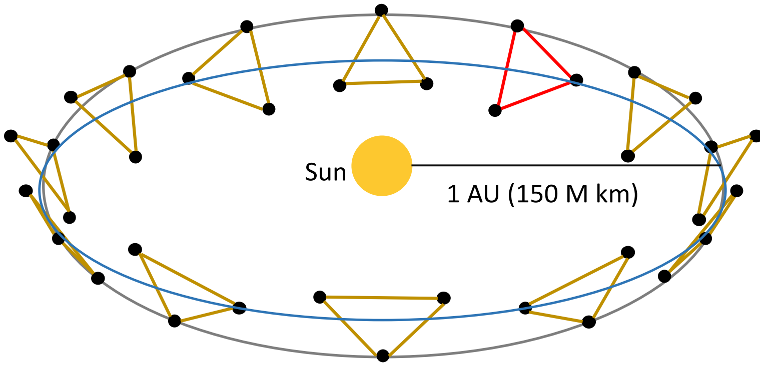

Laser

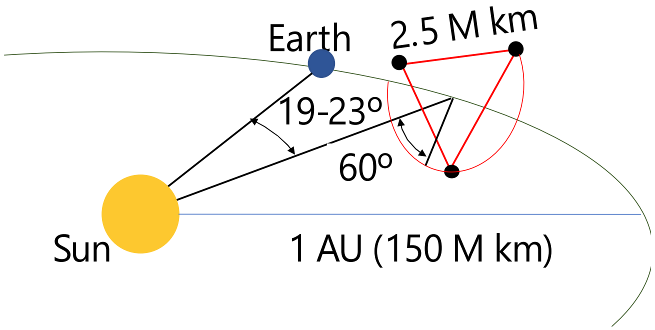

Telescope

# GRAVITATIONAL WAVE DETECTION

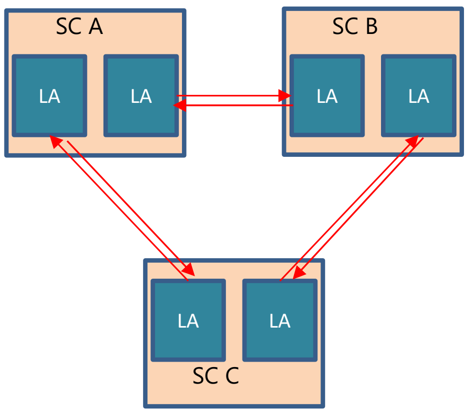
- **LISA (Laser Interferometer Space Antenna)**
  - ESA (European Space Agency)-led mission, ~2034 launch
  - Displacement measurement between "free" masses
    - Concept validated by the LISA pathfinder mission
  - Laser system
    - Candidate US (NASA) component contribution
- **Size of strain *h***
  - $h \sim 10^{-21}$ for typical GW source
    - $L \sim 2.5 \times 10^6$ km (LISA): $L^* h \sim 1$ pm

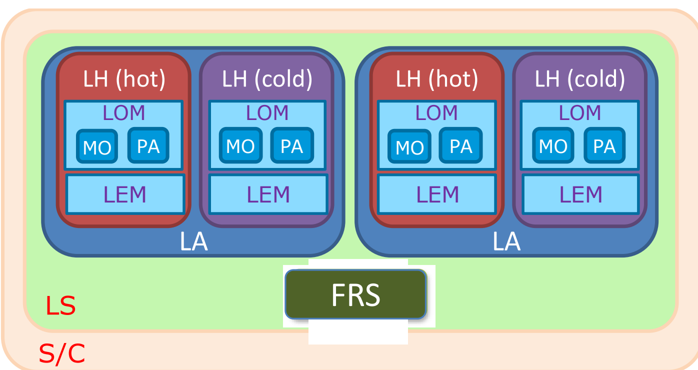


# LASER SYSTEMS FOR LISA AND REDUNDANCY STRATEGY




- **Each Spacecraft (SC) has one Laser System (LS)**
  - Each LS has two Laser Assemblies (LA) and one Frequency Reference System (FRS)
  - Each LA has two Laser Heads (LH) - one hot and one cold redundancy
    - 4 LH per SC, 12 in the constellation.
  - Each LH comprises a Laser Optical Module (LOM) and Laser Electrical Module (LEM)
    - LOM is a Master Oscillator Power Amplifier (MOPA) laser
    - 1 Laser is the master and the remaining 5 are transponders.
- **One Frequency Reference System (FRS) per S/C**
  - Redundancy at constellation level (3 in the constellation)

# TOP LEVEL TRL6 DEMONSTRATOR LASER REQUIREMENTS

- Dimensions 330 × 330 × 250 $mm^3$
- Mass 12kg
- LH dissipated power <75W (TBR)
- LH operating temperature 20±5°C (TBR)
- LH non-operating temperature -20°C to +40°C (TBR)
- LOM Output Power >2W on optical bench (OB) at end of life (EoL)
- Wavelength 1064.50, -0.05/+0.10 nm
- Polarization extinction ratio (PER) >20dB (TBC)
- Lifetime >16 years
  - 6 years on ground with ~1 year for integration and testing, plus 5 years (TBC) of storage
  - 1.5 years TBC OFF state in operational environment (cruise phase)
  - 5 (TBC) years continuous operation in nominal science mode (nominal mission lifetime)
  - 11 (Goal) years continuous operation in nominal science mode (extended mission lifetime)

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# MASTER OSCILLATOR POWER AMPLIFIER (MOPA) ARCHITECTURE & REQUIREMENT

## Master Oscillator

**Low frequency noise**

- Actively controllable to 300Hz/rtHz@mHz

➢ Wavelength as a ruler

**Low Intensity noise**

Shot-noise limited RIN @heterodyne frequency

(5~20MHz)

➢ Shot-noise limited performance

**Phase lockable**

Micro-cycle/rtHz accuracy @mHz

➢ Measurement principle

**~150mW**

## Phase Modulator

**Clock noise transfer**

High side-band phase fidelity

(0.6mrad/rtHz @ ~2GHz)

➢ Accurate clock jitter information exchange

**Phase modulation for cavity locking**

PDH locking to cavity

Tunable offset

➢ Frequency Stabilization

**PN code for ranging**

**Data exchange**

Fiber coupled

**~50mW**

## Power Amplifier

**Intensity controllable**

RIN down to $10^{-4}$/rtHz @mHz, 2W level

➢ Low force noise on test mass through radiation pressure

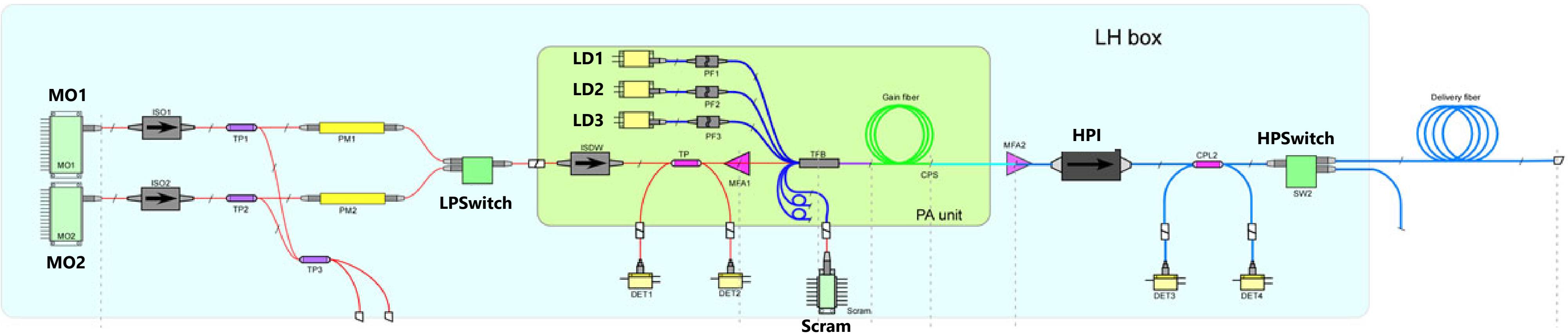
**Maintain sideband phase**

Small differential RF phase noise (0.6mrad/rtHz @ 2GHz)

➢ Accurate clock jitter information exchange

**~2W**

# LISA LASER ARCHITECTURE




- NASA GSFC LISA laser architecture is a Master Oscillator Power Amplifier (MOPA)
- The laser architecture contains the following redundancy –
  - Seed laser subsystem (2X) – 1 hot and 1 cold subsystems, each containing a Master oscillator (MO), a tap Coupler, an isolator, and a phase modulator
  - 808 nm Pump Diodes (2X) – hot redundant and internal to MO
  - 974 nm Pump Diodes (3X) – 1 hot and 2 cold redundant diodes for PA Module
- The *PA* output is transmitted to an output fiber via a high-power isolator (*HPI*) then a 1x2 output switch, denoted as High-Power Switch (*HPSwitch*).

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# STUDY DESCRIPTION

- **Problem Description**
  - The LISA LS is the basis for the measurement system for the proposed LISA mission led by the ESA with a target launch date in ~2035. One of NASA's possible contributions is the laser for the measurement system.
  - The LISA measurement system is designed to measure Gravitational Waves from Massive Black Hole Binary star systems that deform space-time and can be detected as a change in the length of the interferometer arms (~10 pm/Hz$^{1/2}$).
  - Ensuring the appropriate reliability for the LISA LS is a critical challenge. A key performance requirement for the final design ESA selects will be the simultaneous and stable in-orbit operation of 6 laser heads (LH) on three different spacecraft (SC) over a period of 5 years, with a goal 11 years, without any prolonged interruptions.
  - This assessment is to determine if the LS design and development plan is on track to meet the requirements provided by ESA in the TRL 6 demonstrator requirements document.

# SCOPE OF ASSESSMENT

- **Scope**
  - NASA's Goddard Space Flight Center (GSFC) requests that the NASA Engineering & Safety Center (NESC) assess the Technology Readiness Level (TRL) 6 design of the Laser System (LS) for the Laser Interferometer Space Antenna (LISA). The reliability assessment through this effort will, at a minimum, produce an evaluation of the LISA Laser Transmitter reliability, physics-of-failure analysis, identification of failure modes, and screening opportunities for laser components. The effort shall include the following tasks:
    a) Assess the design for weaknesses and suggest improvements to mitigate risks,
    b) Assess the laser reliability plan for weaknesses and suggest improvements to mitigate risks and improve effectiveness, and
    c) Assess the current redundancy plan on laser subsystems for weaknesses and suggest improvements to mitigate risks and improve effectiveness.

# NESC APPROACH

- The GSFC LISA design team formulated a set of specific technical questions ("Statement of Work" Questions) for each of the technology areas in the system to guide these tasks.
- Biweekly meetings with specific topics and discussions led by each technology sub-area lead were held with the NESC panel throughout the study period.
- Each technology sub-area drafted their initial reports to form the basis for the final report. These initial reports were circulated among the assessment team members for comment and technical enhancements.
- No experiments, independent texts, inspections, or associated analysis were performed by the assessment team. The team relied on design data provided by the LISA team at GSFC and open-source data available from manufacturers or the professional literature.

# NESC REVIEW PANEL

| Name | Discipline | Organization |
|---|---|---|
| **Core Team** | | |
| Upendra Singh | NESC Lead | LaRC |
| Stephen Horan | S&I Deputy | LaRC |
| Neal Spellmeyer | Laser/Fiber Comp./Fiber Amp | MIT-Lincoln Laboratory |
| Erik Zucker | Laser Diodes | Erik Zucker Consulting |
| Malcolm Wright | Power Amplifiers (PAs) | JPL |
| Mulugeta Petros | Laser Electronics | LaRC |
| Charles Antill | Laser Electronics | LaRC |
| Matthew Joplin | Radiation Effects | GSFC |
| Joseph Minow | Radiation Effects | MSFC |
| Azita Valinia | Astrophysics | GSFC |
| **Business Management** | | |
| Theresa Barduch | Program Analyst | LaRC/MTSO |
| **Assessment Support** | | |
| Betty Trebaol | Project Coordinator | LaRC/AMA |
| Linda Burgess | Planning and Control Analyst | LaRC/AMA |
| Leanna S. Bullock | Technical Editor | LaRC/AMA |

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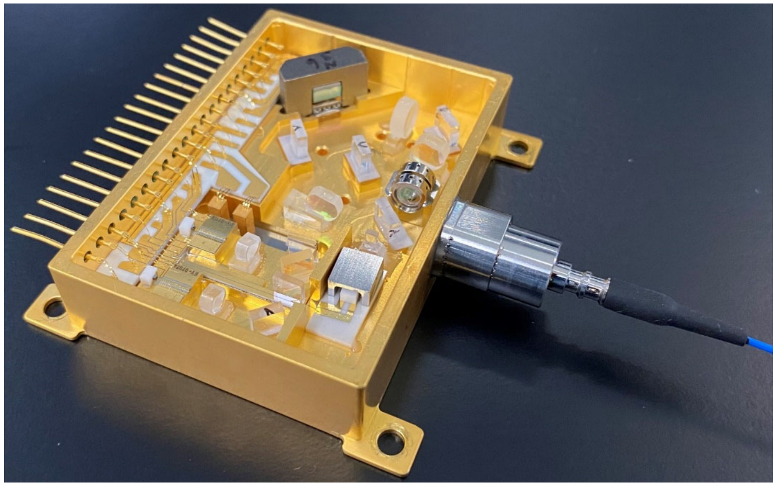
# LASER ARCHITECTURE ASSESSMENT

**Question**: Review the laser architecture and provide feedback on redundancy, derating, and implementation strategies to meet the LISA lifetime and performance requirements.

**Assessment Result**: Given the stringent intensity, frequency, and phase stability requirements, a small non-planar ring oscillator (NPRO) is ideal. The additional steps taken by the team to make the active laser material small is commendable. A shorter cavity length provides a longer free spectral range spacing prohibiting spurious wavelength from appearing along the emission bandwidth. A master oscillator power amplifier (PA) is the best way to meet the 2 W output required.  This type of PA is a fiber amplifier.

# MASTER OSCILLATOR ASSESSMENT

- The MO is based on the non-planar ring oscillator (NPRO[1]) design with a scaled down crystal resonator (~1/4 of original NPRO) packaged in a small, micro Non-Planar Ring Oscillator (μNPRO) assembly
- The MO contains
  - Two 808-nm pump diodes combined to pump the Nd:YAG crystal shaped in a NPRO monolithic resonator
  - The crystal mounts on top of a single TEC for temperature regulation.
  - A piezoelectric transducer (PZT) mounts on top of the Nd:YAG crystal for frequency tuning.





*Ref 1 - Thomas J. Kane and Robert L. Byer, "Monolithic, unidirectional single-mode Nd:YAG ring laser," Opt. Lett. 10, 65-67 (1985)*

# µNPRO MASTER OSCILLATOR ASSESSMENT

**Question:** Review the µNPRO design and provide feedback on redundancy, derating, and implementation strategies to meet the LISA lifetime and performance requirements.

**Assessment Result:** The µNPRO provides the stable, low-noise oscillator for the system. It was selected based on the existence of a prototype that provides required performance with minimal changes to design. Key subsystems are the laser cavity formed around the µNPRO crystal; the 808-nm pump lasers; optics for forming the cavity, coupling the pump to the cavity, and coupling light from the cavity to a single-mode optical fiber; and the laser housing that includes thermal management, hermetic sealing, mechanical structure, and electrical feedthroughs. The LISA Program is working with a vendor to build a TRL 6 µNPRO that will undergo testing, at the unit level and integrated into the LS.

# OBSERVATIONS AND FINDINGS ON MO

| Findings | Recommendations |
|---|---|
| The TRL 6 µNPRO design and operating point is being finalized (e.g., TBCs and TBRs). | • Develop a specific set of requirements and hardware block diagrams representing the planned TRL 6 configuration against which design performance and any necessary changes can be tracked.<br>• Identify the target µNPRO operating current and determine if noise-eater circuitry will be included in the baseline design. |
| The TRL 6 units have challenging reliability and noise performance requirements that can be impacted by design decisions that have not been finalized. | The TRL 6 units should be tested functionally and environmentally to show compliance with requirements. |
| A reduced voltage needed to meet the required Doppler tuning range and resolution can have a significant impact on the PZT drive electronics indicating the selection of a thinned crystal may present a design risk. | Continue working with the µNPRO vendor to achieve a thinned crystal that will reduce the required PZT tuning voltage. |

Observation:

- Given the stringent intensity, frequency, and phase stability requirements, a small NPRO is ideal.

# POWER AMPLIFIER FINDINGS, RECOMMENDATIONS, AND OBSERVATIONS

| Findings | Recommendations |
|---|---|
| The reliability of the optical components in the MOPA design leverages other programs' development. | Baseline the flight design and test of representative optical components at elevated operational levels. |
| There is a risk of optical fiber damage during I&T, which requires an increased fiber length to allow for damage repair. | Outline the test plan for integration of the fiber connectors with the optical head to ensure a low insertion loss and a high temperature rated fiber coating. |
| The gain fiber performance is sensitive to thermal management and potential radiation effects, and rad-hard fiber is only available from a non-US source. | Provide a thermal analysis of the gain fiber thermal management requirement to within 0.05°C. |
| Options exist for the PA 976-nm pump modules that are dependent on final LD vendor selection.<br>• A backup seed laser is being baselined for protection.<br>• A separate source, though improving reliability, adds complexity to the design. | • Investigate the 976nm pump diode vendor options for the pumping architecture (e.g., number of diodes, sparing) and the baseline architecture.<br>• Perform a risk analysis of the seed laser dropout and test the shutdown timing with the SCRAM source. |

# PUMP DIODE SCOPE OF ASSESSMENT

- **Aspects reviewed**
  - Design – Assess the design and usage of the 808-nm (MO) and 976-nm (PA) pump diodes in the NASA GSFC LS
  - Reliability – Review the GSFC Reliability Plan, and test results to date
  - Redundancy – Assess the current redundancy plan for the pump laser diodes
- **Design**
  - The current use of polarization-combined 808nm single-mode pumps enables the highest likelihood for achieving reliability requirements.
  - Transition from 808-nm to 885-nm pumping, if commercially available, should increase reliability.
  - The current use of spatially-combined 976-nm multi-chip pumps should enable excellent efficiency and reliability.
- **Reliability**
  - The 808-nm life test data to date demonstrate feasibility but are not yet adequate to prove acceptable reliability.
  - There were no 976-nm life test data available, but based on industry experience, reliability should be adequate.
  - There were no, or very little, environmental stress data available for either the 808-nm or 976-nm pumps.
- **Redundancy**
  - There is powerful redundancy built into the LS design for both 808-nm and 976-nm pumps.
  - Opportunities should be explored to decrease the allowed FIT budget of other components or subsystems to enable a relaxation in the 808-nm diode FIT budget.
  - There is likely opportunity to reduce the quantity of 976-nm pumps.

# RADIATION SUSCEPTIBILITY FINDINGS AND RECOMMENDATIONS

| Findings | Recommendations |
|---|---|
| Ionizing dose susceptibility in the Yb gain fiber in a passively irradiated, high dose rate test is unclear | Repeat ionizing dose testing on flight lots to quantify variance of degradation and bound worst case analysis |
| Rad-hard electronics have not been selected for laser electronics module update and laser pre-stabilization system electronics | • Enabling COTS components (e.g., PZT driver) have unknown susceptibility to radiation effects and no clear radiation hardened replacement.<br>• Conduct a SEE test campaign on enabling COTS components |

# GENERAL OBSERVATIONS AND RECOMMENDATIONS

- The LISA design team is a capable, experienced group that is actively working to validate the TRL 6 design and identify and burn down risks.
- Challenges faced in transitioning from a TRL 6 design into a flight program include parts obsolescence - the necessary reliance on commercial fiber and electro-optic parts whose availability may change over time.
- The LISA design team needs to create thorough documentation for all elements in the current program to form a clear basis for tech transfer to vendors in the future, and to be able to quickly evaluate needed changes.

- *There were no alternative viewpoints identified during the course of this assessment by the NESC team*

# OVERALL ASSESSMENT SUMMARY

- The overall SME team's assessment conclusion is that there are **no fundamental problems or major design issues that will prevent the LISA team from meeting the ESA requirements** for the TRL 6 demonstrator.
- It must be acknowledged that the **LS design is challenging and there will be development risks that must be addressed moving forward**. There are items that the SME assessment team believes need further consideration, including
  - The LISA design team needs an improved tracking of requirements and hardware configuration in the LS subsystems, e.g., commercial off-the-shelf (COTS) versus radiation-hardened (rad-hard) parts, to ensure that the design closes
  - **Testing protocols for components and subsystems needs to be fully developed** (e.g., functionality, aging, thermal, radiation, etc.) to ensure proper measurements are made and that the design is not affected
  - The assessment team has two major concerns that will need oversight if ESA selects this design: (1) the TRL 6 design is primarily based on COTS parts and the performance specifications or operating characteristics of the replacement rad-hard parts for beyond TRL 6 may perturb the design, and (2) **rad-hard part lead times and obsolescence may affect the design's viability**

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## CONCLUSIONS

- The NASA Laser Team acknowledges the assessment study performed by the NESC team.
- This assessment was sponsored and funded by NESC from August 2020 to July 2021.
- The laser team implemented changes and executing steps to address findings, observations and recommendations from the NESC team.
- The laser team is moving forward to qualify the LS design, which includes the Laser Optical Module and the Laser Electronics module to TRL6 by mid-2024 and prepare to deliver a unit to ESA for evaluation.